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SPY BRISTLE BOT – A VIBRATION-DRIVEN ROBOT FOR THE INSPECTION OF PIPELINES

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ABSTRACT

In this paper, a bristle bot for spying and inspection purposes is presented. It consists of the main body with integrated power supply, vibration motor and inspection technology. It is surrounded by a cylindrical chassis with evenly distributed bristles. The robot is designed for pipelines and tubes with a diameter of 25 mm, but the chassis can be exchanged to adapt the robot for different pipeline sizes. Furthermore a mechanical model of a bristle robot is studied numerically. The locomotion velocity is obtained for different parameter combinations and resistance forces.

Index Terms – bristle bot, vibration robot, pipeline inspection, friction anisotropy

1. INTRODUCTION

Locomotion systems with bristles perform motion due to internal vibrations, which are transformed by bristles to a translocation of the overall system. A great number of natural and technical systems realize the needed asymmetry due to a ratchet-like design of the contact elements [1]. Asymmetric friction forces are achieved. Bristles on a rough surface are an example for such a design. They are established in technical systems, like motors [2], [3], vibratory feeders [4], endoscope cameras [5] and mobile robots. Worm-like locomotion systems (WLLS) are robots with bristles for one-dimensional motion. Technical realizations and analytical models are presented in [6]-[15]. A typical mechanical model for the influence of bristles on the locomotion of the system is an anisotropic coefficient of friction.

Bristle bots are mobile robots. They are excited by the motion of an internal mass, mostly a vibration motor which is rotating an unbalanced mass. They got popular as toys, e. g. self-made from a cell phone vibration motor, a button cell and a tooth brush, [17], [18] as well as scientific research objects [16], [19]. One of the earliest scientific contributions presenting analytical models and prototypes of this kind of robots can be found in [20]. Bristle bots have the great potential to be used as inspection robots for small [21], [22] or big [23] pipelines. A capsuled design can be simply realized, which even makes minimal invasive medical purposes considerable [24] - [26]. Well-known are endoscope cameras using the principle of bristle bots for search and rescue missions [27], [28]. Further bristle robots with a focus on miniaturisation can be found in [29].

2. PROTOTYPE

The prototype is presented in Figure 1. It consists of the main body and a cylindrical chassis with evenly distributed bristles. The chassis can be exchanged in order to adopt the robot to different pipeline diameters. The body in Figure 1 is designed for linear tubes with a constant diameter of 25 mm. The main body consists of three components: the information system, power supply and vibration system. The vibration system consists of a cell phone vibration motor, which is powered by a 220 mAh accumulator with an applied voltage of 3.3 V. It is fixed on the conductor plate, which connects the spy camera with the integrated flash disk and the USB interface for charging and information access. For lighting purpose, two LEDs are installed. The robot has a total mass of 19 g, a length of 85 mm and a diameter of 25 mm. The bristles have an average length of 3 mm with an inclination angle of 30° with respect to the vertical direction.

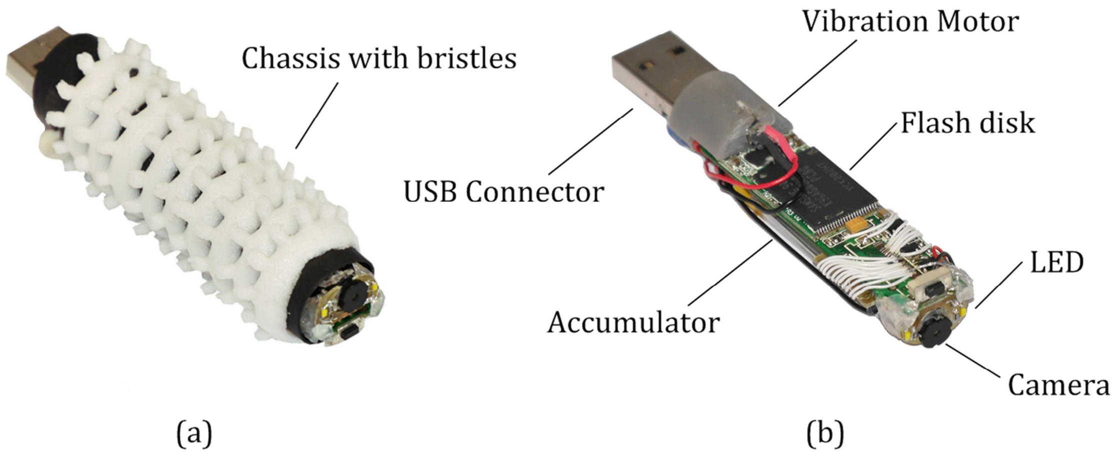

Figure 1: *Design of prototype: (a) overall system, (b) internal electronics*

The configuration of the robot, presented in Figure 1, can move up to 45 minutes with a speed of 1 mm/s. It should be noted that the robots velocity can be increased by increasing the inner excitation (higher frequency, heavier unbalanced mass) and adapting the bristle design in length and angle, as it is discussed in [4]. E. g. the robot for 25 mm pipelines, discussed in [22], can move with a speed of 12 mm/s. It has similar dimensions but longer bristles (8 mm) and a lighter mass (6.7 g).

Figure 2 shows a single frame of a video, made by the robot moving through a tube of glass, which was covered with an opaque material. The LEDs light the environment so that possible damages could be found.

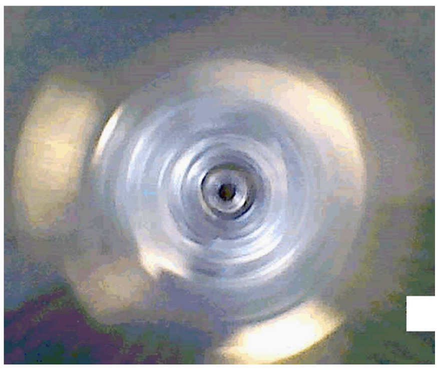

Figure 2: *Single frame of an inspection video made by the prototype*

3. ANALYTICAL MODEL

Bristle bots can be studied using the model presented in [22] and [31]. In this paper the model is modified due to the present studying purpose. The model displayed in Figure 3 consists of a rigid body with mass M, an internal point mass m and a number n of weightless support elements with the length l. The rigid support elements are attached to the main body by rotatory joints and rotatory springs and dampers with the constants c and k. The support elements represent the bristles and have an initial angle φ_0 with respect to the vertical direction. They perform the asymmetry in the system characteristics, which is needed for the locomotion. The endpoints of these elements have permanent contact to the ground. A fixed Cartesian coordinate system $(0xy)$ is introduced.

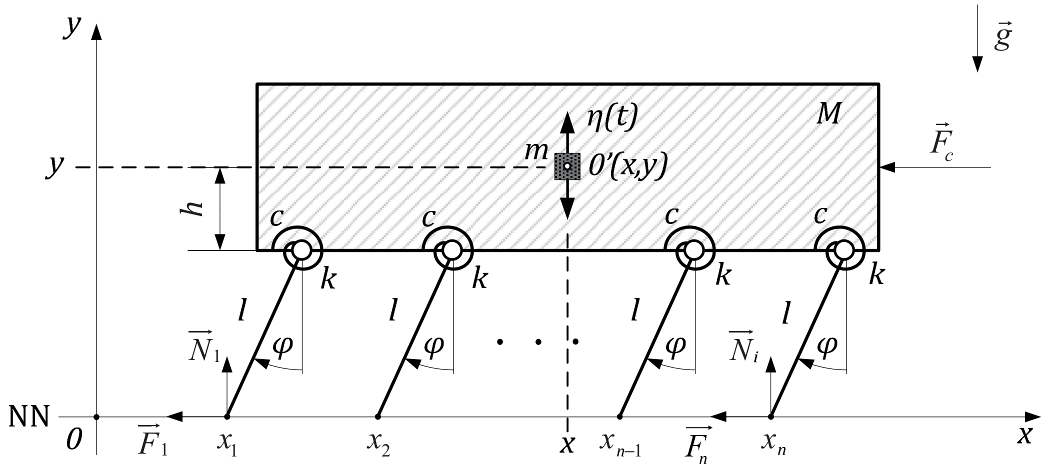

Figure 3: *Mechanical model of a bristle bot*

A kinematic condition prevents the model from tilting and it can be obtained

$$y = h + l\cos\varphi. \tag{1.1}$$

The model is two-dimensional with two degrees of freedom. The internal mass m is excited with the periodic function $\eta(t)$. While moving, the system needs to overcome the constant resistance force F_c. The dry friction forces between the system and the ground are modelled as

$$F_{Ri} = -\mu \frac{1}{n} |N| \, sgn(\dot{x}_i), \tag{1.2}$$

with $i = 1 \ldots n$. All n contact points have the same velocity

$$\dot{x}_i = \dot{x} - l\dot{\varphi}\cos\varphi. \tag{1.3}$$

The normal force is determined by

$$N = (m + M)\left(g - l\ddot{\varphi}\sin\varphi - l\dot{\varphi}^2\cos\varphi\right) + m\ddot{\eta}. \tag{1.4}$$

The coefficient of friction is modelled anisotropic:

$$\mu = \begin{cases} \mu_-, & if\ \dot{x} - l\dot{\varphi}cos\,\varphi < 0, \\ \mu_+, & if\ \dot{x} - l\dot{\varphi}cos\,\varphi > 0. \end{cases} \tag{1.5}$$

The equations of motion are

$$\ddot{x} = -\mu\left(g - l\ddot{\varphi}sin\,\varphi - l\dot{\varphi}^2 cos\,\varphi + \frac{m}{m+M}\ddot{\eta}\right)sgn\left(\dot{x} - l\dot{\varphi}cos\,\varphi\right) - \frac{1}{m+M}F_c \tag{1.6}$$

$$\begin{aligned} &\left(\ddot{\varphi}sin\,\varphi + \dot{\varphi}^2 cos\,\varphi - \frac{g}{l} - \frac{m}{m+M}\ddot{\eta}\right)\left(sin\,\varphi + \mu\,cos\,\varphi\,sgn\left[\dot{x} - l\dot{\varphi}cos\,\varphi\right]\right) + \\ &\frac{nk}{(m+M)l^2}\dot{\varphi} + \frac{nc}{(m+M)l^2}\left(\varphi - \varphi_0\right) = 0 \end{aligned} \tag{1.7}$$

The detailed derivation of the equations can be followed in [22]. A similar model with different studying purpose and friction models can be found in [30].

4. SIMULATIONS

The equations are solved numerically with the MATLAB/Simulink© environment using the parameters of the prototype presented in Figure 1. The motion behaviour is analysed. The displacements of the centre point $0'$ and a leg endpoint are shown in Figure 4 over an interval of five excitation periods. Also overlaid is the normal force. The periodic excitation through the internal mass m results in a periodic motion behaviour of the system. It can be observed that while the centre of the system $0'$ shows a sinusoidal oscillation, the endpoints of the legs move in the forward direction. Since this simulation was done with isotropic friction coefficients, this is the result of alternating normal forces. The unsteady behaviour of the normal force is a result of the signum function in equation (1.2), which is dependent on the velocity of the legs endpoints. Since this velocity is at times close to zero, the sign changes often, due to the numerical integration.

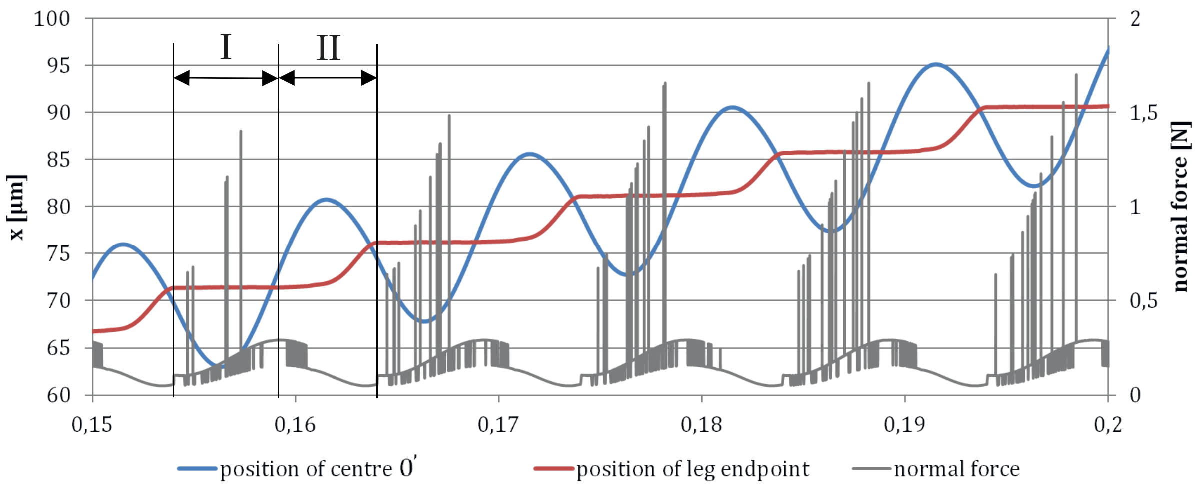

Figure 4: *Characteristic movement over five excitation periods.*
Used parameters: f=100Hz, φ_0=30°, l=5mm, M=19g, µ+=µ-=0.5, m=0.4g, c=30Nmm, Fc=0N

The periodic motion can be separated into two intervals (I & II in Figure 4). In the first interval (I), the main body accelerates towards the ground and the normal forces are increasing. This results in increased friction forces which block the backwards movement of the legs. Since the main body moves towards the ground, it is thus also pushed forward. When the main body accelerates upwards (II) again, the normal forces and the friction forces decrease which allow the legs to rotate back into their initial position. Over one period, the system moves about 5 µm in the forward direction. With a frequency of 100 Hz this results in a total velocity of about 0.5 mm/s.

Below, the influences that selected parameters have on the velocity are studied. Figure 5 shows the influence of asymmetric friction coefficients in combination with a resistance force. μ_+ is varied and denotes the friction coefficient in the forward direction. μ_- is fixed at a value of 0.5 and represents the friction coefficient in the backward direction. It can be seen that a forward movement is even possible when μ_+ is greater than μ_- and there is a counteracting force. In general, the velocities are higher for small values of μ_+ and F_c . If F_c increases the model is accelerated in backward direction.

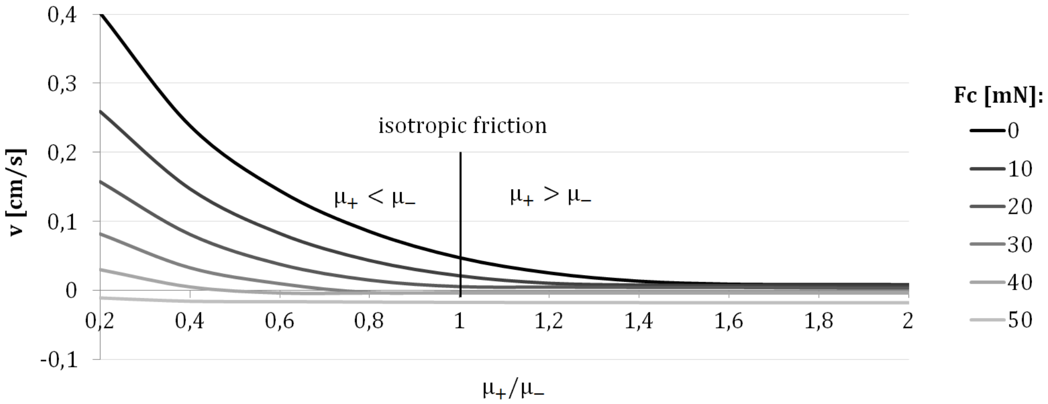

Figure 5: *Influence of asymmetric friction coefficients in dependence of a resistance force Fc. Used parameters: f=100Hz, φ_0=30°, l=5mm, M=19g, μ-=0.5, m=0.4g, c=30Nmm*

Figure 6 shows the influence of varying leg lengths *l* and torsional stiffnesses *c*. Optimal leg lengths for this parameter set seem to be around 10 mm. For legs longer than 5 mm, the studied torsional stiffnesses suggest that higher stiffnesses are beneficial for higher velocities. But this behaviour is reversed for short legs. At 5 mm, the torsional stiffness seems to be negligible for the studied value range.

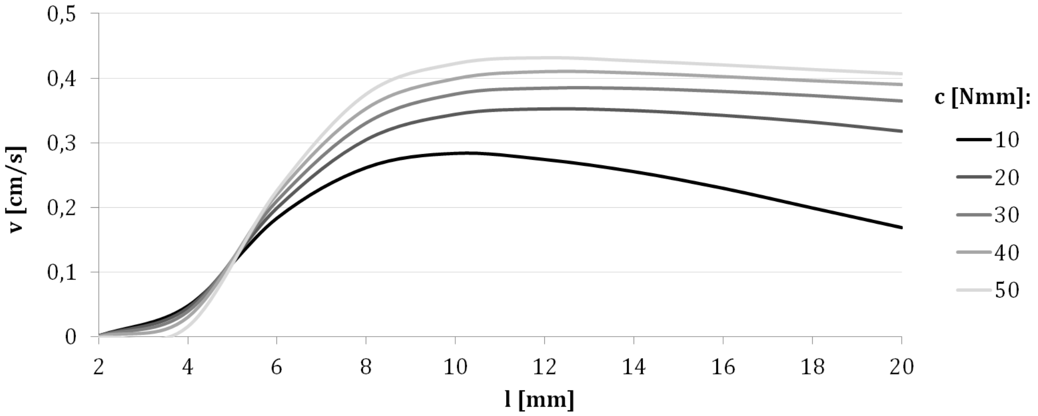

Figure 6: *Influence of leg length l in dependence of the torsion stiffness c. Used parameters: f=70Hz, φ_0=30°, μ+=μ-=0.5, M=19g, μ-=0.5, m=1g, Fc=0*

5. CONCLUSIONS

It is shown, that bristle bots can be used as inspection robots for pipelines. The presented prototype is too slow for real inspection purposes, e. g. in vast pipeline systems of the supply infrastructure of buildings, the main energy systems in ships, submarines, planes or rockets, the chemical industry or the heat exchangers in power plants. The presented mechanical model can be used to improve the robots design. A prototype with a bigger internal mass, a higher excitation frequency and an optimized bristle design can meet the requirements of industrial applications. Faster robots with similar parameters can be found in [22] and [31].

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